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Meeting the Challenges of Deepwater Gulf of Mexico Drilling With Non-Petroleum Ester-Based Drilling Fluids

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Abstract

The search for recoverable hydrocarbons in the Gulf of Mexico has moved into increasingly deeper waters. Since its introduction in the Gulf of Mexico in 1993, the ester-based drilling fluid system has been used on five deepwater wells. This paper describes the applications of the ester-based system and its ability to handle the special challenges of deepwater drilling in the Gulf of Mexico.

Introduction

Since the late 1940s the mainstay of the United States offshore drilling theater has been the Gulf of Mexico. Over the last half century a large portion of recoverable petroleum reserves existing in the shallower water depths of the Gulf has been explored and produced. The search for recoverable hydrocarbons in the remainder of the Gulf of Mexico has been slowed by high project costs and by the lack of technology necessary to drill in these more hostile environments. Drilling engineering success in the design of floating vessels along with innovations in hardware and practices has enabled operators to venture into deeper water depths in their search for commercial quantities of oil and gas.

In the Gulf of Mexico, this search has moved into water depths greater than 1,000 ft (305 m) in the Garden Banks and Mississippi Canyon additions. Historically, deepwater wells in the Gulf of Mexico have been drilled using water-based muds. However, within the last year, a number of deepwater wells have been drilled using an ester-based drilling fluid system.

This particular system has exhibited increased performance in terms of penetration rates and reduced drilling costs. In this paper, field applications of the ester-based drilling fluid in water depths between 1,000 and 4,000 ft (305-1,220 m) are discussed.

References and figures at end of paper.

Deepwater Gulf of Mexico Drilling Fluid Requirements

To drill a well successfully, all drilling fluids should be able to:

- Clean the hole
- Provide adequate barite suspension capabilities
- Stabilize reactive formations
- Maintain stable drilling fluid rheological and filtration properties.
- Control formation pressures.

However, deepwater drilling poses additional challenges for drilling fluid performance. These challenges result from reduced temperatures in the riser and/or upper part of the annulus and from extended distances from the formations being drilled to the surface. In this paper, three salient challenges for deepwater drilling are identified and discussed, namely:

- Gas hydate suppression
- Hole cleaning capability in the riser sections
- Gas solubility in invert emulsions.

Laboratory and field data documents the ability of the ester-based mud system to meet these requirements as a conventional drilling fluid and as a specialized deepwater drilling fluid.

Deepwater Gulf of Mexico Drilling Fluid Selection

Until 1993 the drilling fluids of choice for such challenging environments in the Gulf of Mexico were water-based salt/polymer systems. The polymers employed in these systems for formation stabilization were primarily partially hydrolyzed polyacrylamide (PHPA), polyanionic cellulose (PAC) or other natural and/or synthetic polymers.

The younger shales found in deepwater environments, however, are difficult to drill due to the highly reactive nature of the clays in a water-based environment. This reactivity can result in high polymer consumption rates, high dilution rates, frequent occurrences of bit balling, and slow rates of penetration. These factors coupled with high daily operational costs often produce expensive ventures with daily operational costs running USD 100,000 or more per day. With the advent of ester-based drilling fluids in 1990, operators were given an additional option in the drilling fluid selection process.

Ester-Based Drilling Fluid System

The ester-based system is the product of extensive research conducted to find a suitable replacement for petroleum-based diesel (OBM) and mineral oil-based (LTOBM) invert emulsion systems[1,2,3]. The driving forces in the development of the ester-based system were:

- Compliance with regulations restricting the use of petroleum-based oils
- Reductions in the environmental impact of cuttings discharged into the sea during drilling operations
- Improvement in the working environment for workers on the drilling rigs
- System biodegradability under aerobic and anaerobic conditions
- Absence of bioaccumulation of system components in the benthos and in organisms used in toxicity monitoring
- Performance equal to or better than traditional OBM and LTOBM.

After several years of research and optimization, the system was identified. It employs a vegetable ester as the fluid base instead of petroleum hydrocarbons such as those found in diesel and mineral oils. The particular ester is the product of a annually-renewable vegetable fatty acid reacted with alcohol, as depicted in Figure 1.

To date, the ester-based drilling fluid system has been used to drill approximately 80 wells and over 500,000 ft (152,000 m) in the UK[4], Dutch, and Norwegian[5] sectors of the North Sea, Asia, Australia, Africa and the United States. Use of

the ester-based system in deepwater drilling applications has centered in the Gulf of Mexico.

Field Experience with the Ester-Based System in Deepwater Gulf of Mexico Wells

Five deepwater wells have been drilled to date with the ester-based drilling fluid in the Garden Banks and Mississippi Canyon additions in the Gulf of Mexico. The approximate locations of the wells are shown in Figure 2.

Well A, the well with the shallowest water depth, was drilled in 1,000 ft of water. The well was the most highly-deviated of the five, with a horizontal displacement of 13,780 ft (4,201 m). Well A was drilled with the ester-based system from 9,770 ft (2,979 m) to 18,480 ft (5,634 m), with a 9⅝-in liner set at 15,825 ft (4,825 m) as planned. Drilling time was 117 hrs for the 12¼-in interval and 57 hrs for the 8½-in interval. Average penetration rates for the two intervals were 52 and 47 ft/hr, respectively. During the cementing of the liner at well TD, a partial loss of returns were noted when pumping ceased for pump repairs. When circulation was resumed, mud loss was encountered.

Well B was drilled from a semi submersible in 1,544 ft (471 m) of water in late 1993. A total of 3,292 ft (1,004 m) of 8½-in hole was drilled in 92.5 hours with the system, giving an average ROP of 39 ft/hr (12 m/hr). A maximum mud density of 15.5 lbm/gal (1.86 SG) was used on this well, the highest of any ester-based fluid used in deepwater to date. A saltwater kick was encountered on this well which required a sidetrack to be drilled.

Well C was drilled from a semi submersible in 2,945 ft of water in early 1994. The 8½-in interval was drilled from 13,814 ft (4,211 m) to 17,760 ft (5,415 m) in 111 hours. Average ROPs were 35 ft/hr (10.7 m/hr). Mud densities for this slightly deviated interval reached 14.3 lbm/gal (1.72 SG). No problems were encountered drilling this well.

Well D, drilled in the same location as Well C, was drilled from a semi submersible in 2,945 ft (898 m) of water in early 1994. The 9⅞-in interval was drilled from 11,610 ft (3,540 m) to 18,920 ft (5,768 m) in 126 hrs, giving an average ROP of 58 ft/hr (17.7 m/hr), an increase in average ROP of 66 percent over that of Well C. The hole deviation was only slightly greater than that of Well C. The maximum mud density for this interval was 14.1 lbm/gal (1.69 SG).

The operator saved an estimated 16 days of planned drilling time, which amounted to a considerable savings on overall well cost. In addition, exceptional formation stability provided by the ester-based drilling fluid allowed the operator to omit a planned liner from the well program, resulting in signficant additional savings.

Well E was a exploration well drilled in 3,994 ft (1,218 m) of water. A total of 3,651 ft (1,113 m) of 10⅝-in hole was drilled at an average ROP of 111 ft/hr (34 m/hr). A liner was then set and cemented. After drilling out the casing shoe, 1,099 ft (335 m) of 8½-in hole was drilled at an average ROP of 80 ft/hr (24 m/hr). Mud losses were then encountered and the ester-based system was displaced from the well.

In summary, a total of 28,008 ft (8,539 m) of hole have been drilled with the ester-based drilling fluid system in Gulf of Mexico deepwater wells. Hole sizes have ranged between 12¼-in and 8½-in with mud densities between 10.0 and 15.5 lbm/gal (1.2-1.86 SG). Operators have incurred significant cost savings in terms of drilling time, liner requirements, and elimination of borehole instability problems.

Hole Cleaning Capabilities of the Ester-Based Drilling Fluid System

The excellent hole cleaning capabilities of ester-based muds have been previously documented[5]. They were shown to have elevated yield stresses

at colder temperatures and less viscous characteristics at higher temperatures and pressures. The flow indices of ester-based muds were high (0.8-0.95), values that indicated improved hole cleaning under the eccentric drillpipe in highly-deviated sections.

On the Gulf of Mexico deepwater wells the ester-based system's low shear rate fluid rheology was monitored and products were added to maintain desired properties. Figure 3 contains a plot of several hole cleaning parameters for Well A in Mississippi Canyon:

- API yield point (YP)
- FANN® 35 viscometer 3 rpm dial reading ($\theta 3$)
- Yield stress (Yield-Power Law rheological model parameter τ_0[6])
- Low shear rate yield point (LSR YP).

A brief description of the Yield-Power Law rheological model is found in Appendix A. Appendix B contains information on the calculation method and use of the low shear rate yield point.

On Well A, no hole cleaning problems with the ester-based system were reported, even though the intervals drilled were highly-deviated (65-70° from vertical). These deviation ranges are usually considered to be among the most difficult to clean. With the exception of the YP, all hole cleaning parameters track each other very well. Figure 3 shows mud carrying capacities of 5-12 lb/100 ft^2 were used to clean the two intervals drilled. Values of the τ_0 yield stress parameter used in drilling the Gulf of Mexico wells are found in Table 2.

As is evident in Figure 3, the API YP does not track the three low shear rate hole cleaning parameters very well. This is because the API YP is valid only when the drilling fluid's Flow Index (n) value = 1, something not often found in drilling fluid characterization. In this paper, the API YP should not be confused with the yield stress (τ_0) term used to evaluate mud carrying capacity.

Hole Cleaning in Risers with the Ester-Based Drilling Fluid

Hole cleaning and cuttings suspension in the large diameter risers used in deepwater drilling is an area of concern. The inability of drilling fluids to remove cuttings collected in large diameter sections where annular velocities are low often results in packing-off problems, sometimes referred to as "gumbo attacks". In deepwater drilling, the drilling fluid in the riser is subjected to cold temperature and low pressures.

To better understand the performance of the ester-based system under these conditions, extensive laboratory testing was performed using the FANN 70 high temperature high pressure testing apparatus[5]. The results were used to construct a computer model to predict downhole rheological properties at varying temperatures and pressures. That work predicted that the fluid's yield stress values in the riser at 39°F (4°C), 160 psi (11 bar) were about 2-2½ times that of the fluid's yield stress as measured on surface at 120°F (49°C).

To better simulate the conditions in deepwater Gulf of Mexico drilling, an ester-based system having a density of 13.3 lb/gal (1.6 SG) and an ester/water ratio of 85/15 were tested on the FANN 70 unit using the same protocol employed earlier. A second rheological model was constructed to predict downhole fluid properties at varying temperatures and pressures.

Figure 4 shows the measured and predicted values for the ester-based drilling fluid at five different locations in the riser and at three different temperatures. For the 85/15 ester/water ratio fluid at 40°F (4°C), increases in yield stress values between 1½-2 times the values measured at 120°F (49°C) are calculated. The temperature of 40°F (4°C) was arbitrarily chosen to simulate a very cold fluid in the riser.

Yield stress predictions were also made at 65°F (18°C), a level arbitrarily chosen to simulate a warm fluid in the riser. Modeling shows that yield stress values will fall somewhat with

increases in temperature, but are still adequate for good hole cleaning. Modeling also shows that fluid yield stress values at cold temperatures are sensitive to the effects of pressure, even when these pressures are low (i.e., less than 3000 psi [207 bar]).

Simulation of ester-based fluid yield stresses under low temperature/low pressure conditions shows the system exhibits good carrying capacity and suspension properties, something especially important in large diameter risers where annular velocities are often low.

Barite Suspension Capabilities of Ester-Based Drilling Fluids

Incidents of barite sag were reported only on the highly-deviated Well A in Mississippi Canyon where two intervals were drilled at 65-70° from vertical. The four reported incidents of barite sag were connected with changes in rheological properties before and after running a liner. No incidents of sag were reported while drilling. Mud density variations while circulating were 0.7 lbm/gal (0.08 SG) above or below the original mud weight.

Figure 5 shows the relevant hole cleaning parameters measured at 150°F (66°C) or calculated for the reported incidents of sag. The data shows that barite sag occurred when yield stress (τ_0) values calculated for 150°F (66°C) were 6.0 lb/100 ft^2 or less. Yield stress values were calculated below 6.0 lb/100 ft^2 on the other wells referenced in this paper, but the deviation angles of the wells were insufficient to promote the occurrence of barite sag. Earlier work[5] has related the occurrence of barite sag to yield stress values below 6.3 lb/100 ft^2, but this was for properties measured at 120°F (49°C), not 150°F (66°C).

Stabilization of Reactive Formations

The ability of invert emulsions to stabilize reactive formations has been proven in thousands of wells drilled throughout the world. These fluids usually consist of oil or ester as the continuous phase and $CaCl_2$ brine as the discontinuous phase. The brine provides the osmotic dehydration forces that stabilize the formations being drilled.

The wells in Mississippi Canyon and Garden Banks were drilled in reactive formations that contain large amounts of smectite clays. These formations are known for their borehole instability potentials in even the best of water-based muds. While drilling with the ester-based system, the formations remained stable and caliper logs indicated guage to close-to-guage boreholes.

Stability of Ester-Based Drilling Fluid Properties

The ester-based fluids provide very stable rheological and filtration properties. Table 2 lists selected properties for the five deepwater Gulf of Mexico wells referenced in this paper. In none of the wells did rheological properties become unstable. The system's rheological properties remained stable with the incorporation of formation drilled solids up to 15.1 percent v/v (137 lbm/bbl [390 kg/m^3]) as occurred on Well A. On this well, drilled solids contamination peaked between 15,850-17,600 ft (4,832-5,366 m). Figure 3 shows that stable yield stress values of the ester-based fluid were reported during this time of contamination.

Plastic viscosities of the ester-based drilling fluid systems were also very stable. Figure 6 contains a plot of the PV values vs depth as reported for Well A. As was seen for the yield stress values in Figure 3, high levels of drilled solids contamination did not affect PV values much either. Stable PV values were also reported for an ester-based fluid having a greater density. Figure 7 contains a plot of plastic viscosity versus depth of the system used on Well D in Mississippi Canyon. PV levels were stable and generally remained close to 40 cP (measured at 120°F [49°C]). PV values on the other three deepwater wells were reported in the 35-50 cP range as well.

API HPHT filtration rates of the ester-based drilling fluids were stable on all five wells and are listed Table 2. Usually, these values were reported at 200°F (93°C). Filtration rates for Well D, measured at 200°F (93°C), are depicted in Figure 8 and show that filtration rates were stable and low.

Gas Hydrate Suppression

Drilling fluids must be formulated to discourage or eliminate the formation of gas hydrate crystals. Gas hydrates are a solid phase composed of water and low-molecular-weight gases (predominantly methane) that form under conditions of lower temperature, higher pressure, and gas saturation[7,8]. As drilling moves into deeper waters, the conditions of higher pressures and lower temperatures that promote the formation of gas hydrates are more likely to occur.

The mud system of choice for Gulf of Mexico deepwater drilling in recent years has been a water-based mud designed to stabilize reactive formations and suppress the formation of hydrates by incorporating salt, predominantly sodium chloride into the water fraction. These salt/polymer systems are generally formulated with 20 percent NaCl which provides reasonable suppression values[9].

Invert emulsion systems formulated with a brine-based water phase can offer hydrate suppression superior to that of typical water-based salt/polymer systems. The salinity levels of the water phase in invert emulsions are usually high enough to suppress hydrate formation. In addition, the reduced water content of invert emulsions compared to those of water-based fluids further reduce the ability of gas hydrates to form. In the case of ester-based muds, ester is used as the continuous phase and brine (calcium chloride) as the discontinuous phase.

Testing for the formation of hydrates indicated that an invert emulsion formulated with a 28.83-wt percent $CaCl_2$ brine would provide excellent protection from the formation of gas hydrates. In the test, no hydrates were formed when mud temperatures were reduced to 10°F (-12°C) at pressures of 1,000 psig (69 bar)[10].

Gas Solubility

The ability of an invert emulsion drilling fluid to entrain dissolved gas at downhole conditions can delay identification of an influx of gas on the rig. This "dampening" of indicators such as pit volume gain is not as likely to occur in water-based fluids. At the same pressure and temperature, a barrel of water will contain only ± 1 percent of the gas that could be contained in a barrel of oil[11].

The amount of gas that can be dissolved into an oil or ester is controlled by temperature and pressure. As pressures and temperatures increase, the amount of gas that can be dissolved into an invert emulsion drilling fluid increases. The gas-oil ratio (GOR) is defined as the amount of gas in cubic feet that can be dissolved into one stocktank barrel of oil.

When pressures are released, dissolved gas can come out of solution. This phenomenon is referred to as a bubble point. Bubble points are defined by the certain temperature/pressure conditions under which they occur. It is best for a fluid to release gas under higher temperature and pressure conditions, so more time is available for kick identification and well control operations before the gas reaches the surface.

Tests have been performed to compare the ability of diesel and the base ester to solubilize and release methane gas under conditions of temperature and pressure. The protocol used in the tests with the ester closely followed those used earlier for diesel[11]. For varying GOR values, the bubble points of diesel and the base ester were measured with temperature and pressure. Figures 9 and 10 depict the results. Figure 9 shows the results at 100°F (38°C) and Figure 10 shows the results at 300°F (149°C).

For the data at 100°F (38°C), the results show that for gas-oil ratios of 130-720, the diesel and ester will release gas at nearly the same pressures. There is not much difference between them. However, at 300°F (149°C) significant differences become apparent. For gas-oil ratios of 350-725, the bubble points for the ester are 600-1000 psi (41-69 bar) higher.

For well control reasons this observation is important. For example, for a vertical well circulating 14.0 lbm/gal mud at 300°F (149°C) on bottom, the methane gas will come out of the ester at a depth 800-1,400 feet deeper than it will come out of the diesel. Extra time to detect the gas influx and act is gained.

Flowline temperatures of the five wells drilled in deepwater with the ester-based drilling fluid varied according to bottomhole temperature and riser/casing size and length. Pertinent water depths, mud densities, and temperatures for the five deepwater wells are given in Table 1. During the drilling of these wells, gas was encountered as is typical when drilling gas bearing formations, but no problems with gas solubility/well control were reported.

Conclusions

- The ester-based system can fulfill all of the basic requirements of drilling fluids. Fluid rheological and filtration properties are stable, and the ability of the ester-based system to stabilize reactive formations has been documented throughout the world.

- The ester-based drilling fluid provides good borehole stabilization properties in formations known for their reactivity. Hole instability problems did not occur in the young reactive formations on any of the five wells drilled in Gulf of Mexico deepwater projects.

- Gas hydrate formation in ester-based systems formulated with calcium chloride is less likely to occur than that in water-based muds. Laboratory testing and field observations confirm this observation.

- The base ester releases methane gas more readily at higher pressure and temperature than does diesel. Consequently gas kicks at elevated temperatures and pressures should be more readily detected.

- The ester-based drilling fluid is especially suited for deepwater environments. The system promotes good hole cleaning and suspension properties, suppresses gas hydrate formation, and exhibits improved conditions for well control compared to diesel-based OBM.

- The unique cuttings transport characteristics of the ester-based system provide excellent carrying capacity. The combined effects of temperature and pressure increase yield stress values in the risers, which in deepwater drilling are surrounded by cold water. High pump rates or riser "boosting" is not required in deepwater drilling with ester-based systems.

- Considerable cost savings can be incurred with use of the ester-based drilling fluid system. Not only does the system offer good borehole stability in reactive formations, but it also promotes accelerated penetration rates. These factors can reduce drilling costs on large, expensive projects. Under the right conditions, a well's planned casing program can be changed to eliminate a string of casing or a liner altogether, further reducing well costs.

- Ester-based drilling fluids have proven to be top performers in two of the most difficult drilling environments known today: extended-reach and deepwater drilling.

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Appendix A

Yield Power Law (YPL) Rheological Model

The flow and suspension properties of drilling fluids are usually described using the Bingham Plastic and Power Law rheological models. However, drilling fluids in the intermediate to low shear rate zone (0-1200 sec^{-1}) are more accurately described using the Yield-Power Law (or Herschel Bulkley) rheological model[5,6,12,13].

This model is essentially a merger of the Bingham Plastic and Power Law models, and under certain conditions the YPL model reduces to the Bingham Plastic and Power Law models.

According to the YPL model, the relationship between a pseudoplastic fluid's shear stress and shear rate is given by:

$\tau = \tau_0 + K\gamma^n$, where

- τ_0 is the yield stress. This parameter describes a fluid's carrying capacity and suspension capabilities when shear rates are zero. Conceptually it is identical to the Bingham Plastic model's yield point (YP). But for field muds τ_0 is nearly always lower than the API YP. When a fluid's flow index value = 1, the YPL model reduces to the Bingham Plastic rheological model, and only then will YP and τ_0 values be the same.

- n is the flow index. This parameter describes the relationship between shear stress and shear rate for a pseudoplastic fluid once the effect of yield stress has been accounted for. Conceptually it is identical to the Power Law model's n factor, though calculated values for n using the YPL model will nearly always be higher. This is because the YPL model does not require a shear stress value of zero when shear rates are zero. The only time the YPL and Power Law models will have identical values of n is when τ_0 values are zero.

- K is the consistency index. This parameter describes the viscosity of a pseudoplastic fluid. It is conceptually identical to the Power Law model's K parameter, though once again calculated values of K using the YPL model will nearly always be different from those calculated using the Power Law model. When n values = 1, the YPL model reduces to the Bingham Plastic model and only under that condition will the calculated values of K and PV be the same. When τ_0 = 0, the YPL model reduces to the Power Law rheological model, and only then will the values of K calculated by the two models have the same value.

Appendix B

Low Shear Rate Yield Point (LSR YP)

The low shear rate yield point is calculated using the Bingham Plastic model. It is essentially an adaptation of the API YP, where the $\theta 6$ and $\theta 3$ dial readings from the FANN viscometer are used in place of the $\theta 600$ and $\theta 300$ dial readings to better approximate a fluid's yield stress. API YP and LSR YP are calculated by:

API YP:	$(2*\theta 300) - \theta 600$	(1)
LSR YP:	$(2*\theta 3) - \theta 6$	(2)

The LSR calculation method is quick and does not require a computer algorithm for solution as does the YPL τ_0. However, the method's accuracy is only as good as the $\theta 6$ and $\theta 3$ dial readings with which it is calculated. One drawback to this method is that only an approximate yield stress value is derived. No information regarding the fluid's flow character (i.e. n, K, PV) is available.

SI Metric Conversion Factors

bbl	x	1.589 873	E-01	= m^3
ft	x	3.048*	E-01	= m
in	x	2.54*	E+00	= cm
cP	x	1.0*	E-03	= Pa.s
lb/100 ft^2	x	4.788 026	E-01	= Pa
lbm/US gal	x	1.198 264	E+02	= kg/m^3
psi	x	6.894 757	E+00	= kPa
°F		(°F-32)/1.8		= °C

Nomenclature

BP	Bingham Plastic rheological model
GOR	Gas-oil ratio
K	Consistency index
LTOBM	Mineral oil-based invert emulsion drilling fluid system
n	Flow index
OBM	Diesel-based invert emulsion drilling fluid system
PV	API plastic viscosity
ROP	Penetration rate
SG	Specific gravity
YP	API yield point
YPL	Yield-Power Law (Herschel-Bulkley) rheological model
γ	Shear rate of fluid
τ	Shear stress of fluid
τ_0	Yield stress
θ	Dial reading on viscometer

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TABLE 1
Deepwater Gulf of Mexico Well Information

Well	Area	Hole Size [in]	Max. Hole Angle [° from vertical]	Flowline Temp. [°F]	Average ROP [ft/hr]	Interval Length [ft]	Bit Type	Water Depth [ft]
A	M.C.	12¼ 8½	70 70	120 120	52 47	6,055 2,655	Rock	1,000
B	G.B.	8½ 8½ (ST)	30 30	93 93	38 45	1,131 2,161	PDC	1,544
C	M.C.	8½	15	76	35	3,946	PDC	2,945
D	M.C.	9⅞	21	76	58	7,310	PDC	2,945
E	M.C.	10⅝ 8½	0	68	111 80	3,651 1,099	PDC	3,994

M.C. - Mississippi Canyon
G.B. - Garden Banks

TABLE 2
Typical Ester-Based Mud Properties Reported While Drilling

Well	Mud Density [lbm/gal]	PV @ 120°F [cP]	Yield Stress [lb/100 ft²]	HPHT Filtrate [cc/30 min, 500 psi]	Water Phase Salinity [mg/l $CaCl_2$]	Ester/ Water Ratio	Low Gravity Solids [% v/v]
A	10.0-12.5	21-33*	5-10*	3.4-4.4	325,000	73/27	3.9-15.1
B	15.5	40-49	4-9	2.2-4.0	225,000	84/16	2.3-5.5
C	14.3	34-40	4-8	2.0-2.8	215,000	82/18	1.8-4.2
D	14.1	28-40	4-10	2.0-2.4	215,000	80/20	1.6-5.2
E	13.7-15.1	35-42	6-15	2.0-3.0	210,000	80/20	1.7-5.5

* at 150 deg F (66 deg C)

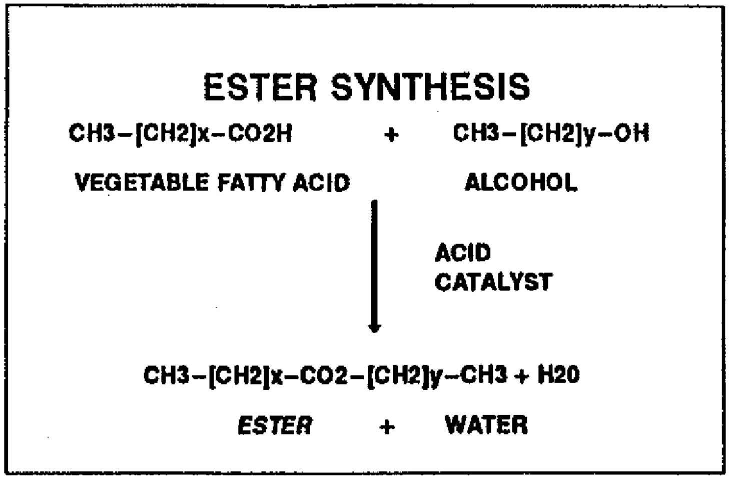

Figure 1. Schematic of Base Ester Synthesis.

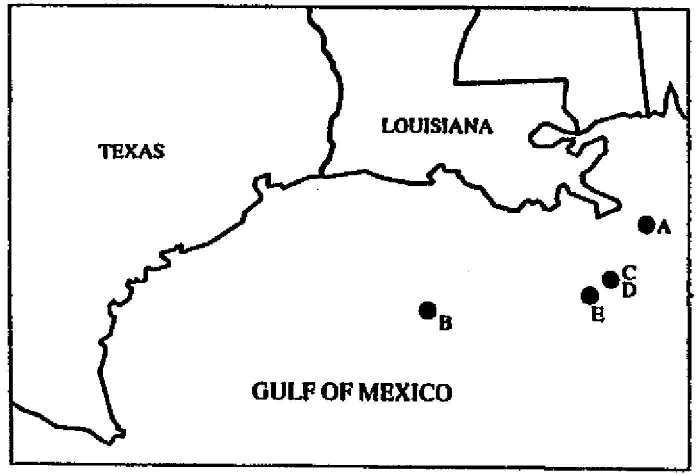

Figure 2. Approximate Locations of Gulf of Mexico Deepwater Wells.

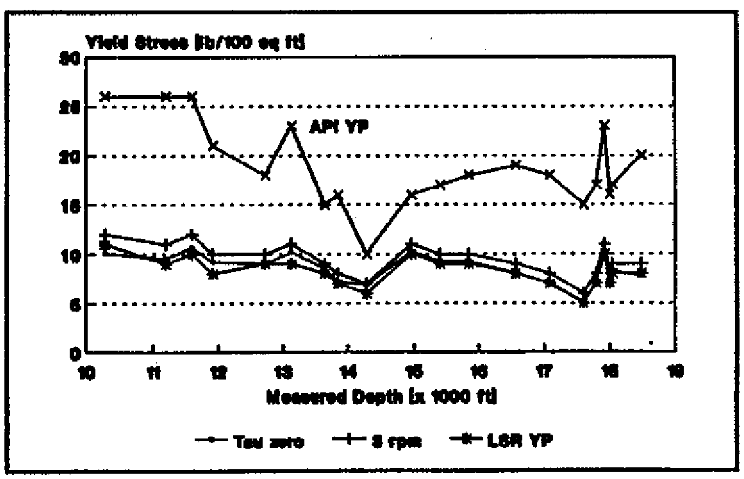

Figure 3. Mud Carrying Capacity Parameters and API YP vs Measured Depth, Well A.

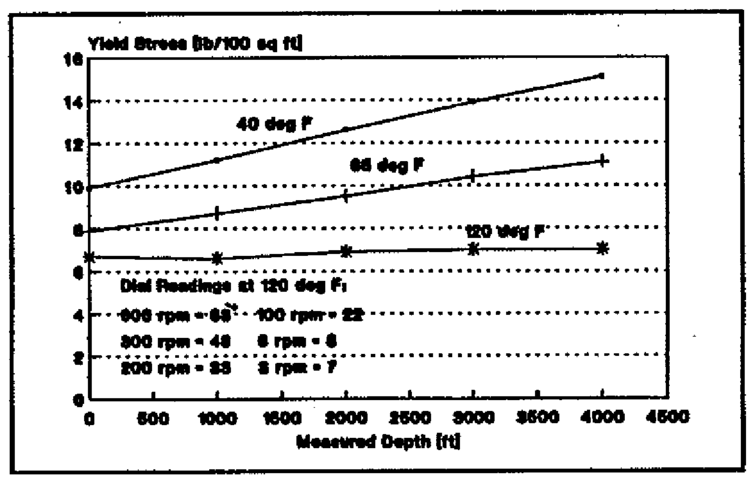

Figure 4. Predicted YPL τ_0 Values in Riser, Well E.

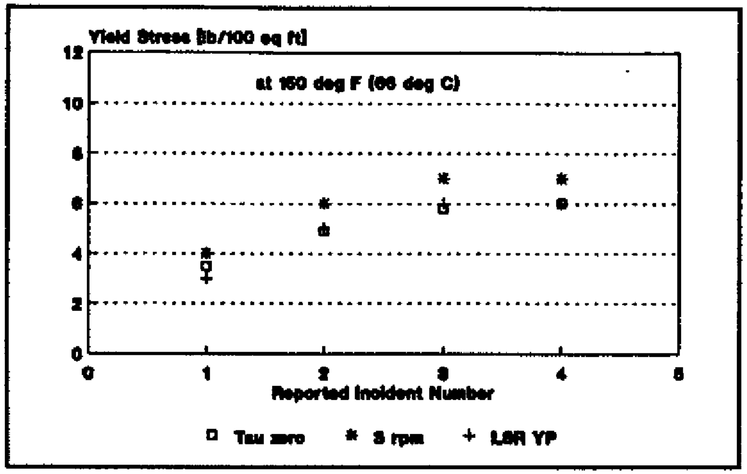

Figure 5. Reported Incidents of Barite Sag vs YPL τ_0, Well A.

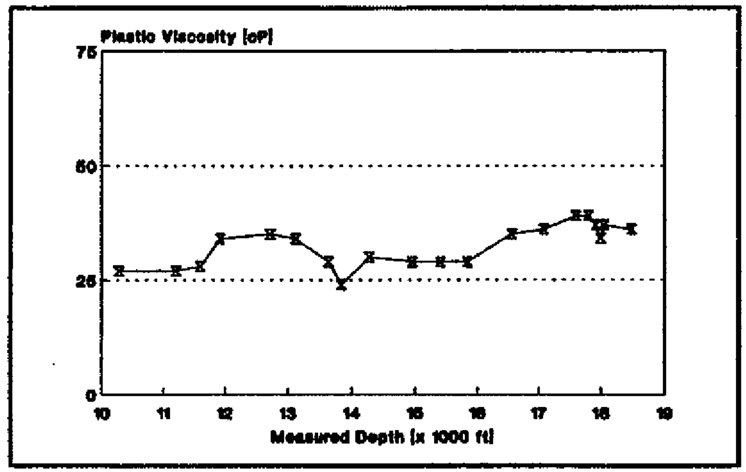

Figure 6. Plastic Viscosity vs Measured Depth, Well A.

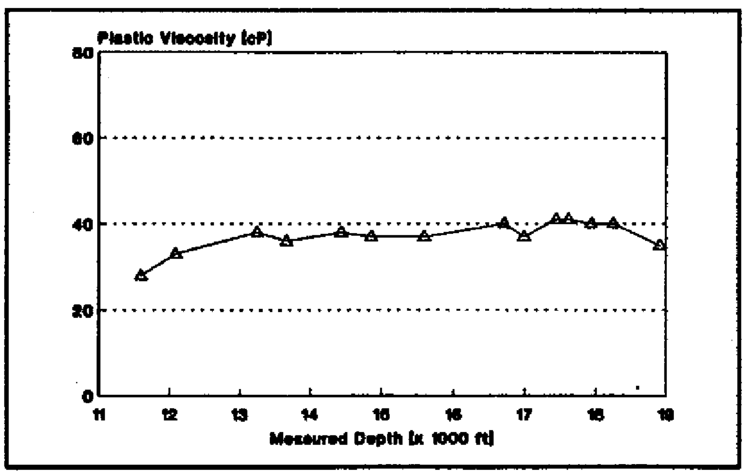

Figure 7. Plastic Viscosity vs Measured Depth, Well D.

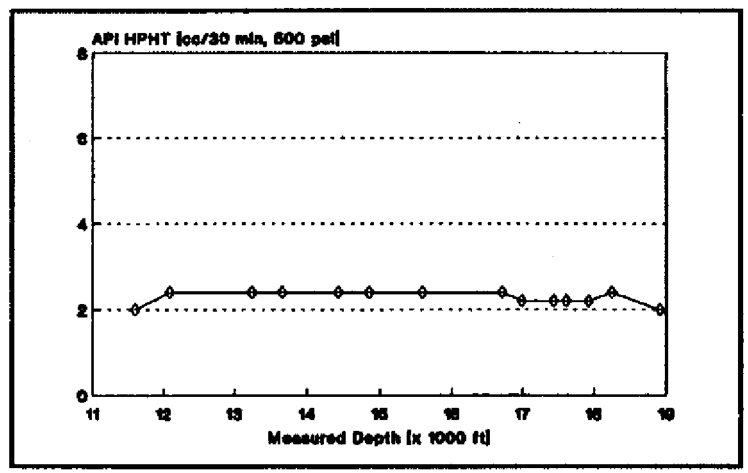

Figure 8. API HPHT Values vs Measured Depth, Well D.

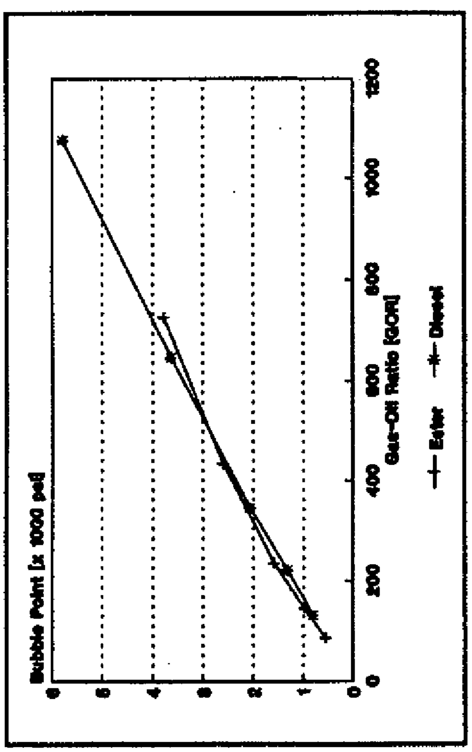

Figure 9. Bubble Points of Diesel and Ester vs Gas-Oil Ratio at 100°F (38°C).

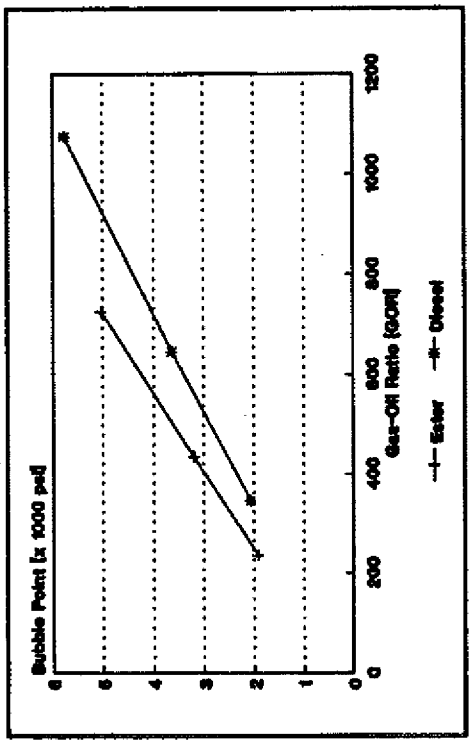

Figure 10. Bubble Points of Diesel and Ester vs Gas-Oil Ratio at 300°F (149°C).